Naturalness and EWSB

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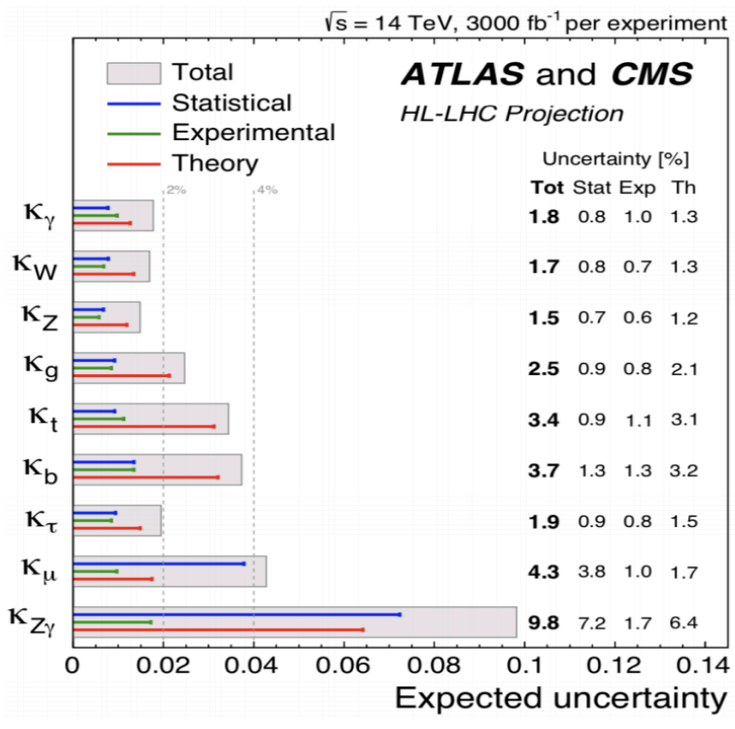
The big open questions that beg for BSM

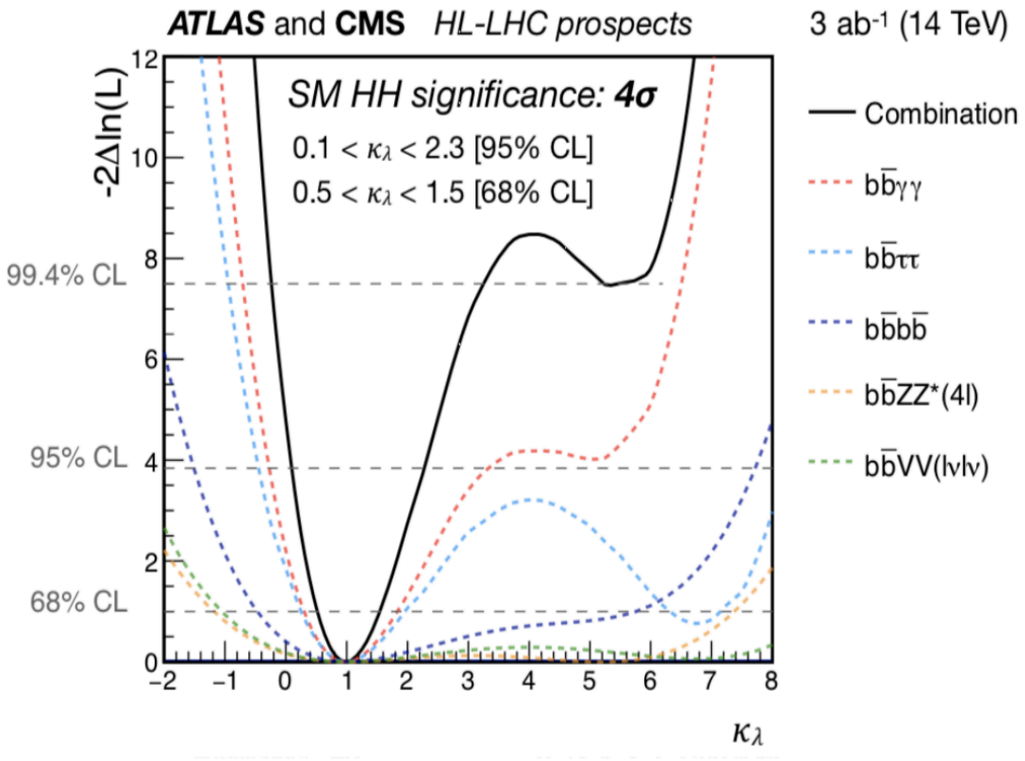
- Data driven: DM, Neutrino masses, Matter vs antimatter asymmetry, Dark Energy
- Theory driven: naturalness, origin of fermion families ….
- Address some of the above questions:
  - Measure exhaustively the Higgs boson properties/interactions
  - Direct BSM searches [e.g. SUSY, heavy exotic particles, ..]
  - Precise determination of the EKW/top observables
    - Which level of precision is necessary?
    - Flavour physics, …

- Landscape at the end of HL-LHC
- Probe new resonances (particles) up to ~8 (~4) TeV

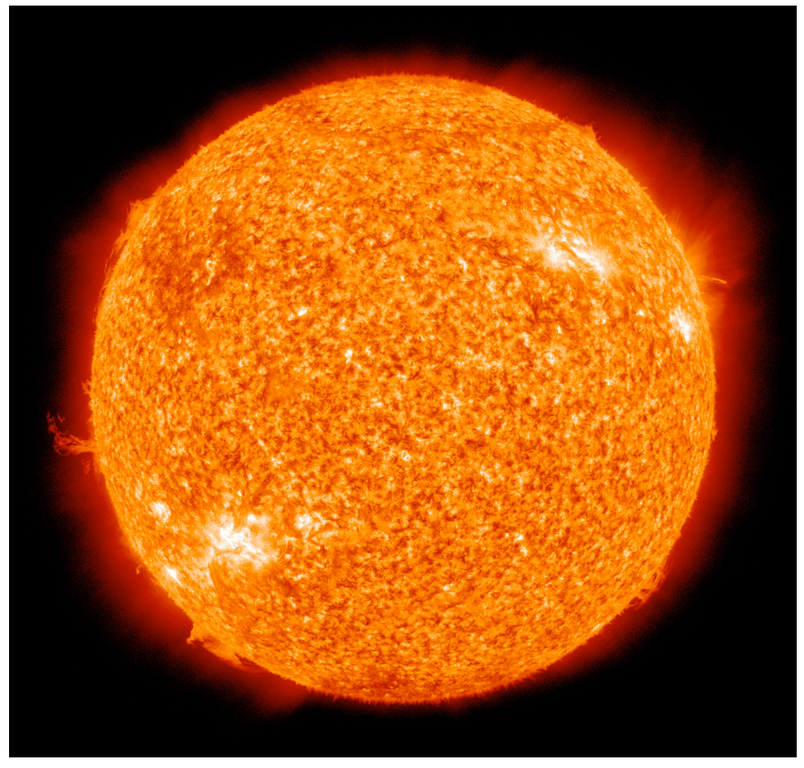
Higgs couplings



Higgs self-coupling



The Electroweak Hierarchy



- Weakness of gravity relative to particle physics: crucial for the world around us: $M_\odot \sim M_{\rm Pl}^3/m_p^2$.
- Without a small Higgs VEV (in Planck units), no big stars or planets.
- The big question:
  Where did the electroweak hierarchy come from?
  The Standard Model gives no answer!
- **Naturalness**: we want a model where we can *calculate* where the Higgs scale comes from, without putting in tiny or huge numbers "by hand" as in the Standard Model.
  [e.g., supersymmetry, composite Higgs, neutral naturalness, ….]

Possible future colliders

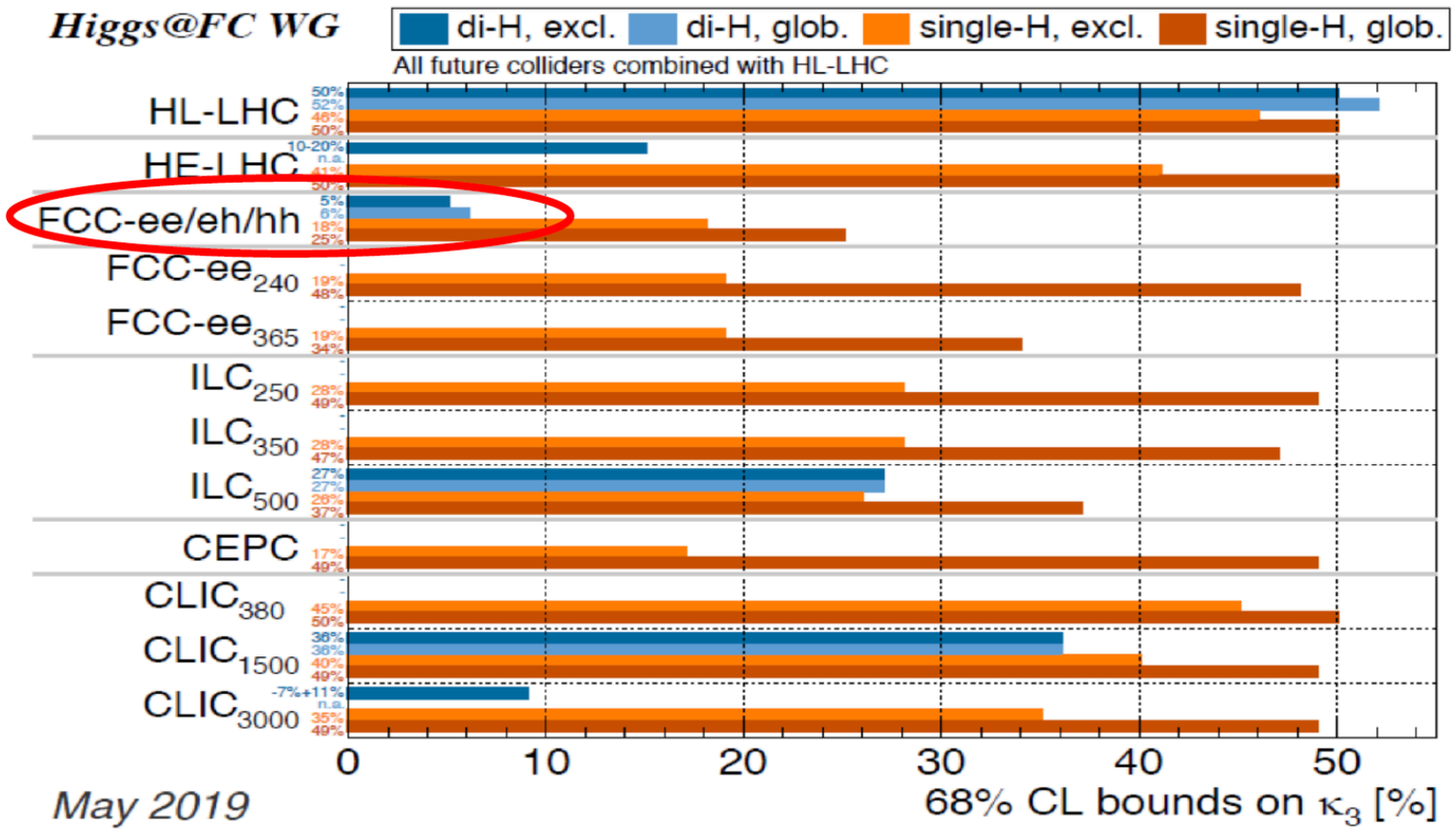
- Where is New Physics:
  - **within LHC reach but "hidden" in difficult corners of the parameter space and/or very small cross section**
  - **Beyond the LHC reach => very massive new particles**
- Both cases: new colliders are necessary to continue exploring the TeV-regime
- Guiding principles for future experiments:
  - Sensitive tests of standard models (SM) parameters
    - "precision" not necessarily the same as "sensitivity"
  - Explore as much as possible different set of scenarios
  - Two approaches [not necessary mutually exclusive]:
    - High precision: lepton colliders (e+e-)
    - Larger rates/ mass reach: hadron colliders (pp, ep, HI)

Indirect probe of BSM physics

- **Measure Higgs self-coupling** is of fundamental importance.
  - Challenging: very small x-section
  - Destructive interference in SM Can be significantly modified in BSM

Ref: 1905.03764

- HH coupling down to 5% for the full FCC program
- Improvement of a factor ~10 wrt HL-LHC;



- **Single-H couplings**
- Full FCC program:
- All couplings better than 1% level ==> order of magnitude improvement in precision with respect to HL-LHC
- Couplings to W/Z and Inv. down to 10^{-3}
- Allows to probe small modifications to Higgs couplings from BSM
  - **What kind of BSM?**

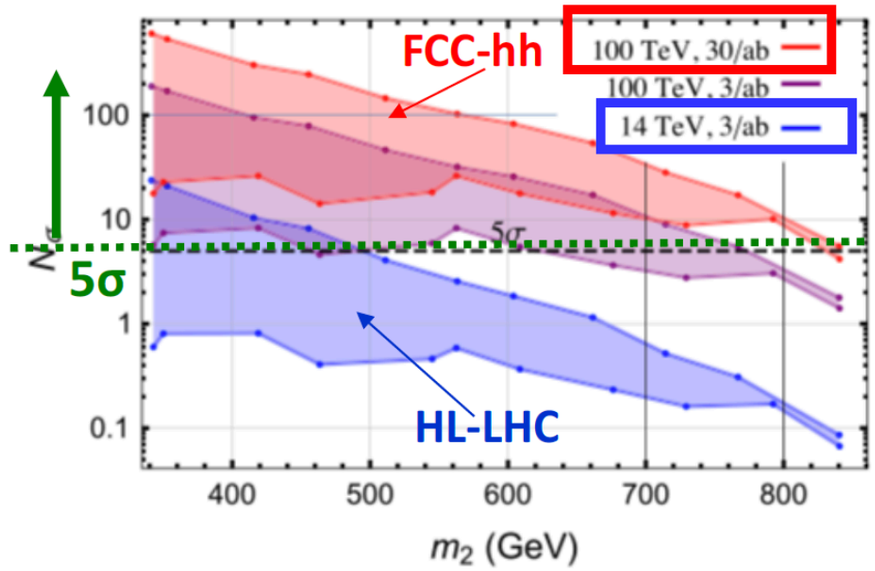
Indirect probe of BSM physics

- **Matter-antimatter asymmetry** Possible explanation: new elementary particles produced through EWSB
  - "violent" transition to the broken symmetry: 1st order phase transition
  - New particles typically ~TeV scale
  - Small cross-sections (~fb)
- Simplest extension to SM: additional singlet scalar
  - Two Higgs-like scalars: h1 (m=125 GeV) and h2
    - Modification of Higgs self-coupling (~few %) and in the Zh1 associated production
      - Direct production of scalar pairs -> Resonant Di-Higgs production
- **Measurement of Higgs properties at % level or better, essential**

Deviation from SM Higgs couplings

- Modification on Higgs self-coupling
- Direct probe with FCC-hh
- Indirect at FCC-ee from a global fit on single Higgs data

Discovery potential in resonant Di-Higgs searches

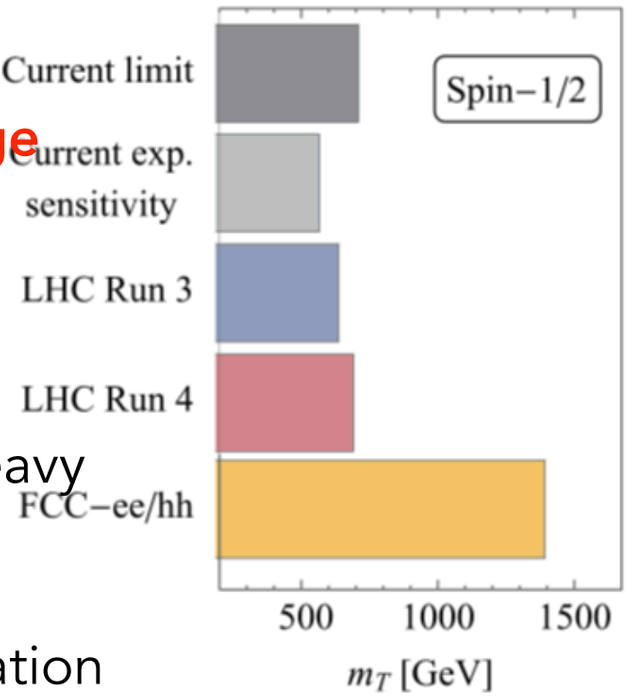


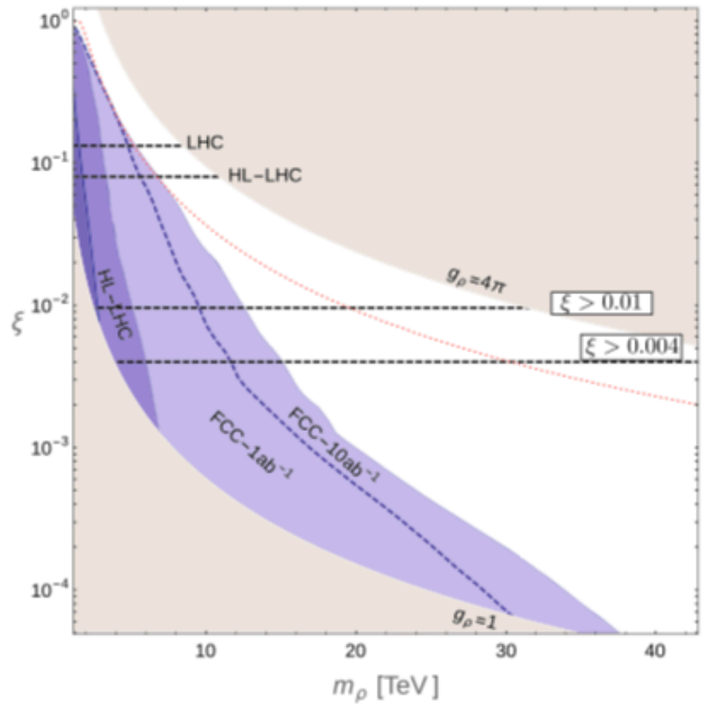
- FCC-hh discovery potential over the entire viable parameter space

Direct searches

- The origin of m_H and the associated hierarchy problem is still a fundamental question
- **Option A: Higgs is an elementary particle ==> SUSY**
- No signs of SUSY at the LHC Either: too heavy – beyond (HL-)LHC reach or in difficult corners of the SUSY parameter space
- Top squark reach with FCC-hh
  - All hadronic; large ME_T
  - Dedicated top-tagging algorithm
- Reach the m_{stop}~10 TeV milestone with FCC-hh @ 30 ab-1

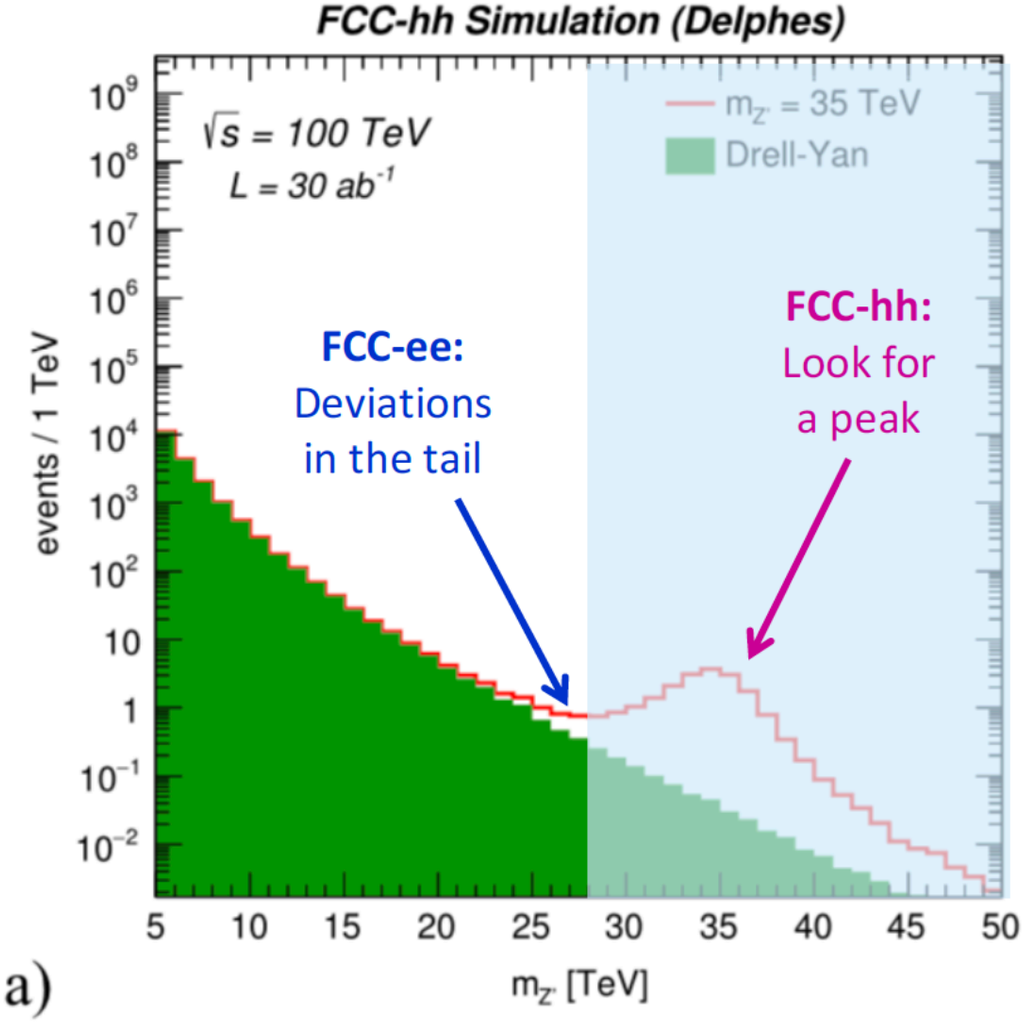
- **Composite Higgs ==> Predict new gauge interactions and new fermions**
- Search based on:
- Direct searches ("bump hunt") for new heavy resonances
- Global fits on Higgs data looking for deviation from SM predictions

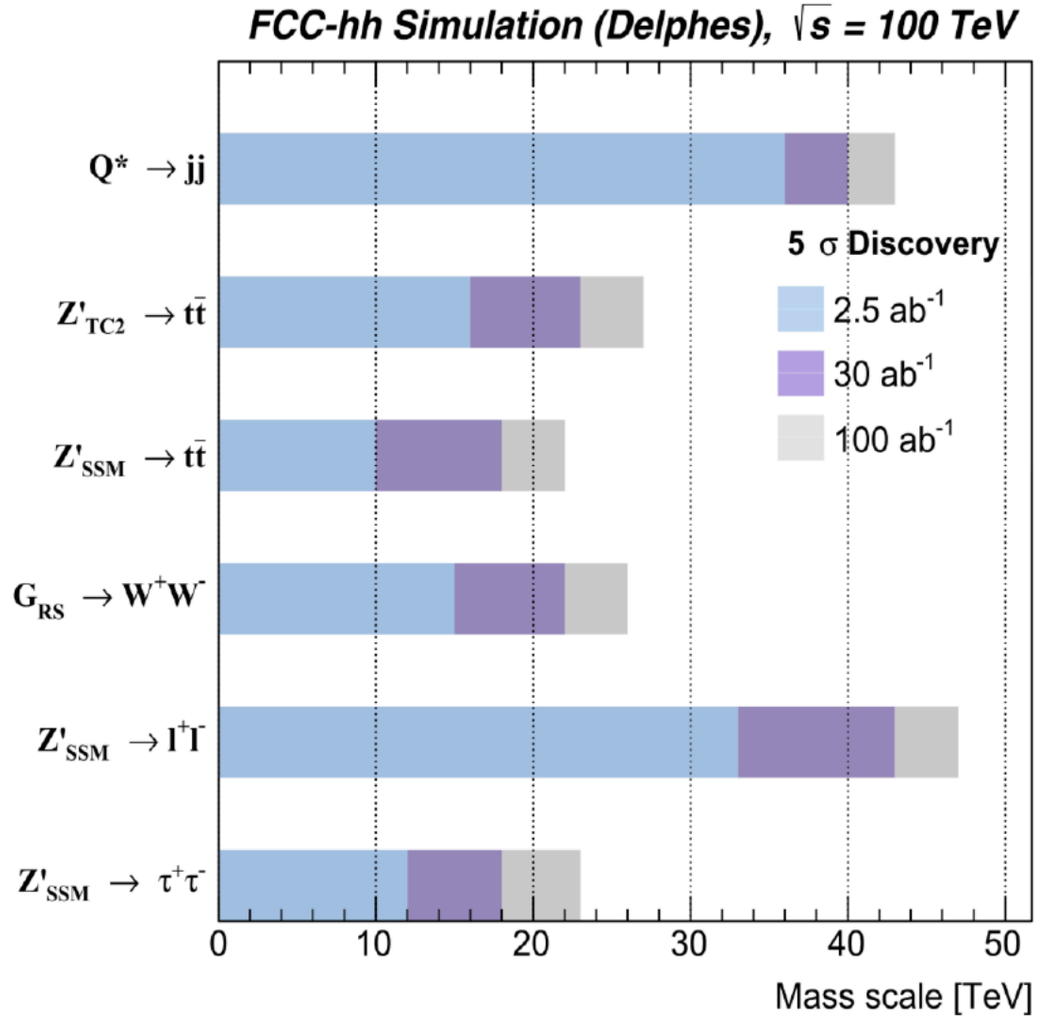




Heavy resonance searches

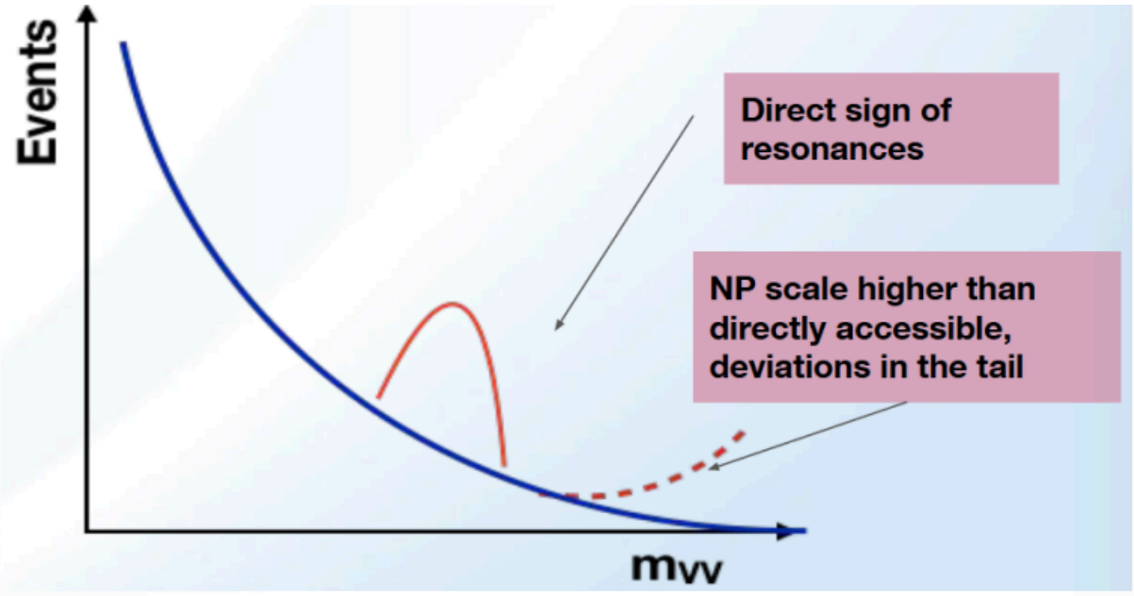
- Exotic resonances/particles/forces
- Multi-TeV objects: “stress-test” for detector design/performance and object reconstruction techniques
- Higgs factories [indirect]: no bump but search for deviations from SM in the tails
- FCC-hh [direct]: “classical” bump-hunt search





Direct vs indirect BSM search: experimental point of view

- The on-going direct new physics searches, which make use of boosted reconstruction to look for high mass resonances, don't need to constrain the uncertainties, as they are looking for peaks over a smooth background in the high invariant mass spectrum, where statistical uncertainty dominates.



- Currently at the LHC the uncertainties related to the large-R jet are of the order of 10% and go up to 50% for pT of the jet of 500 GeV.
- To reach the precision needed for the indirect searches more precise calibration need to be performed
- At the same time the background estimation techniques need to be re-evaluated, currently they have large degree of freedom in the high mass ==> better use of large statistics in pre-defined control regions
- Higgs factories can obviously constrain better systematics

The meso-tuned option

- Naturalness as probabilistic reasoning: theories that easily produce universes looking like ours are more likely to be true than theories that don't (*all else being equal*).
- **Heuristic, not precise: naturalness can't give us definite bounds.** The basic paradigm might be right, and the universe still accidentally looks a little tuned.
- Leads to paradigms like split (or "mini-split") SUSY or, broadly, "meso-tuned" models.

100 GeV	1 TeV	100 TeV
Higgs, W, Z	Gauginos	Squarks, sleptons

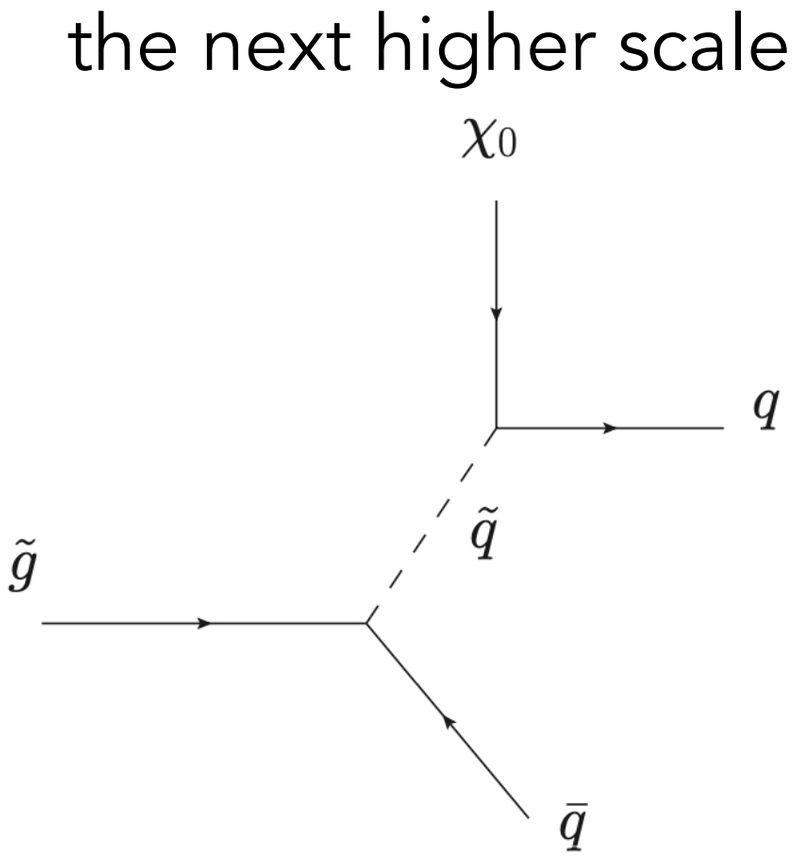
Better for flavor, moduli problems. $M_{scalar} >> M_{gaugino}$ falls out of many top-down models. **Easier to get a 125 GeV Higgs.**

Direct searches for split SUSY

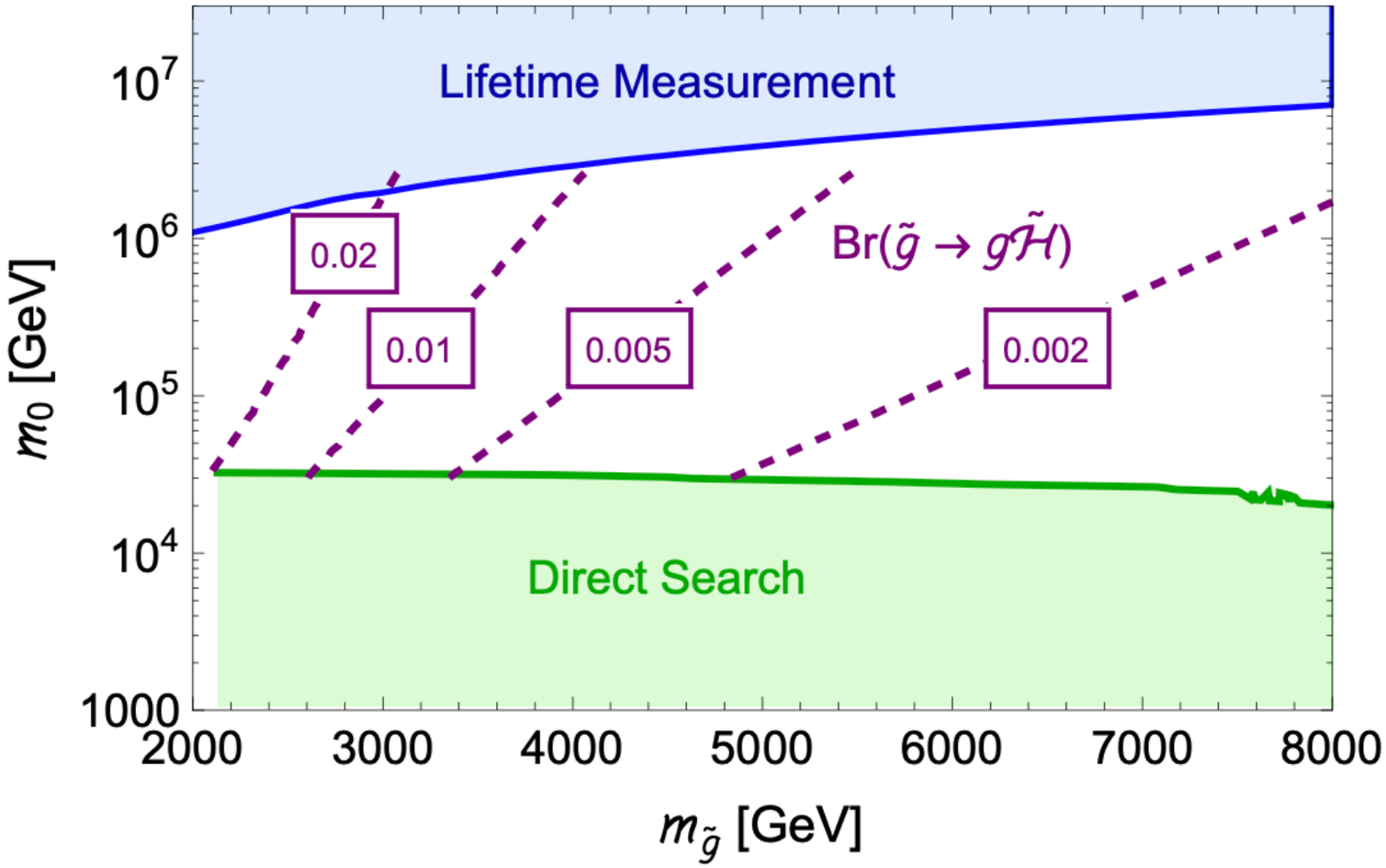
- The hierarchy $M_{scalar} >> M_{gaugino}$ affects searches.
- Gluinos can have a long-lifetime. Displaced vertices:

$$c\tau \approx 10^{-5}\mathrm{m}\left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^{4}\left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^{5} .$$

- Want to not just discover one particle, but use it to learn about the next higher scale.



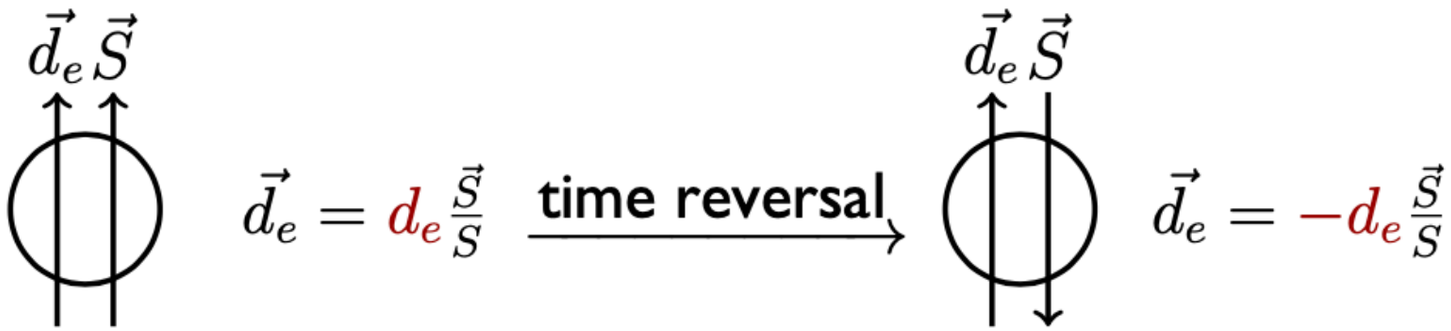
Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski ’12



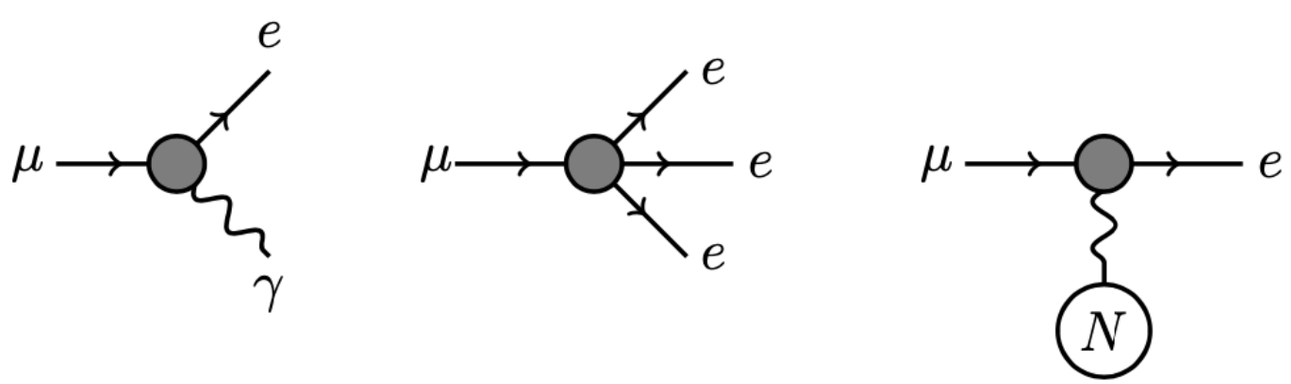
Agrawal, Fan, Reece, Xue, ’17

Clues from CP or flavor experiments?

- Electric dipole moments (EDMs): violate CP



- Charged Lepton Flavor Violation (CLFV)



[thanks to Qianshu Lu for figures]

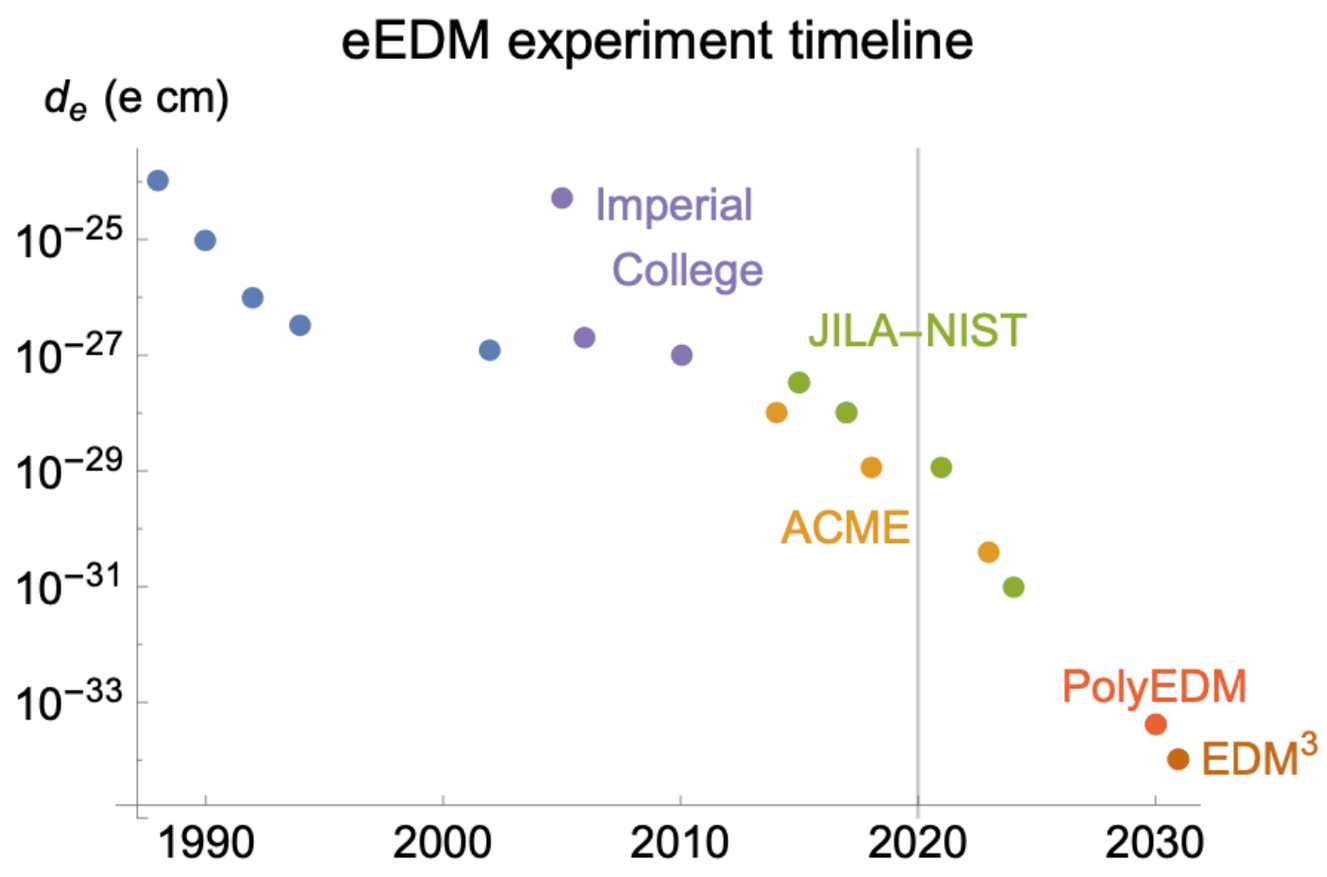
- Could provide indirect evidence for new physics *involving the Higgs boson*.

EDMs and CLFV: the Higgs connection

- Chirality-violating effects ⇒ necessarily involve the Higgs. True of both the EDM and $\mu \to e\gamma$
- Operators like $h^\dagger \ell_i \bar{\sigma}^{\mu\nu} \bar{e}_j B_{\mu\nu}$
- Rapid experimental progress:

Within 10 years, EDM will probe 1-loop new physics at ~PeV, 2-loop at ~50 TeV

CLFV probing ~10-100 TeV scale (depending on flavor model)



[figure from Qianshu Lu]

Thoughts for discussion

- What kind of BSM models can we exclude with the level of precision that we expect on EFT parameters at Higgs Factories?
  - Are those already probed directly at the LHC?
- Direct new physics discovery at Higgs Factories:
  - ALPs, RH ν's, … (what else?)
- If NP is out of reach also for new hadron colliders at which level of precision can we probe EFT parameters given the high systematics?
- If a high-precision test of CP or flavor physics tells us there is new physics involving the Higgs, what's the best way for colliders to follow up and tell us what's really going on?
- Theorists: can we correlate ideas about naturalness, meso-tuning etc. with other observations (e.g., in cosmology)?
- ….. **Please raise your hands. We hope to hear many thoughts, so please limit your comments to 2 minutes!**

Backup